

THE DETECTION OF THE ELECTRIC FIELD VERTICAL DISTRIBUTION
UNDERNEATH THUNDERCLOUD : PRINCIPLE AND APPLICATIONS

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ABSTRACT

During the Florida 89 experiment at Kennedy Space Center a new system was used in order to obtain the vertical distribution of the electric field underneath thunderstorm. It consists of a standard shutter field mill at ground level and five other field sensors suspended from a cable fastened to a tethered balloon located at the altitude of about 1,000 m. It also includes a reception station for telemetered information transmitted by the sensors in altitude and a processing system in order to store data and real time display on a screen the simultaneous field variations at each level and the instantaneous electric field profile. The first results obtained show the great importance of the knowledge of the electric field vertical distribution. The field detected at a height of 600 m reaches 65 kV/m while that at the surface does not exceed 5 kV/m. The field intensity in altitude is a better criterion in determining the right moment to launch a rocket devoted to flash triggering. Using Gauss's law the simultaneous field variations at several levels are used in order to evaluate charge densities. Average values close to 1 nC/m² are calculated in layers up to 600 meters. The calculation of different average charge densities leads to characterize the layer between cloud and ground just before the leader propagation in the case of a cloud-to-ground flash.

1. INTRODUCTION

The electric field largely varies with altitude below a thundercloud. It has been suggested by Wilson [1] that the field increases with altitude because of corona ions produced at the surface. Field measurements above ground using free balloons [2 and 3], tethered balloons [4] and insulating cables [5] show a greater intensity (and sometimes even of opposite polarity) than at the surface. At ground level the field intensity is larger also above water which leads to conclude that the charge layer created by ground coronae has a great influence on the surface electric field [6, 4, 2 and 5]. The only way to detect evaluate and avoid this influence is to measure the field intensity above and across this layer.

On one hand, the vertical electric field distribution provides a good information on the evolution of corona ions from the ground. According to Vonnegut [6], these ions carried up by convective currents can markedly participate in cloud electrification. Unfortunately, no measuring system has been run yet in order to continuously detect the electric field within the first hundreds of meters. On the other hand, the rapid variations of the instantaneous electric field profile are a very useful element for the interpretation of the characteristics of the leader propagation, like channel geometry, velocity. As a matter of fact, Idone and Orville [7] reported a

speed increase and a reduction of the channel tortuosity with height for the upward leader and they suggested that this observation might be related to larger fields in altitude.

Furthermore, since the surface field intensity alone is not always the best instantaneous indicator of cloud electrification [5], a permanent monitoring of the vertical field profile brings a helpful contribution for the purpose of lightning flash warning and triggering.

In order to help to solve these problems we have developed a system conceived to measure the electric field at the surface and at five levels above it. The sensors aloft are designed to be suspended from a tethered balloon and to transmit the data by telemetry. The whole system has been built to be used during the Florida 89 experiment at Kennedy Space Center. It can display in real time the six superimposed field variations renewed every minute and the vertical field profile renewed every second.

Some of the results obtained from the Florida 89 experiment on August 10 1989 are reported in this paper. In the late afternoon of August 10 a thunderstorm was advected from the West and developed over the site propagating easterly. Due to the long duration of the event, the lifetime of sensors batteries did not allow us to record data during the whole thunderstorm. During this event several lightning flashes were triggered by rockets from the ground and from the Lightning Strike Object (L. S. O., described in the next section) located 150 m above ground. The electric field data processing leads to a satisfactory description of the charge layer evolution during the thunderstorm lifecycle and up to 600 m. The electric field is considered positive in the layer above ground when it is created by a negatively charged cloud.

2. THE MEASUREMENT SYSTEM

2.1 THE SYSTEM CONFIGURATION

The tethered balloon where the sensors were suspended during the Florida 89 experiment was carried out by the American company L. T. A. (Lighter Than Air) of Florida. This stream-lined 570-m³ helium balloon is maintained in a convenient orientation in relation to the wind even when it lies on a mooring system at the ground. The figure 1 shows the whole system in the exact configuration of the experiment mentioned before. It is important to note that in this display the scale is respected for the distances between each element but not for their size. The main tether is exclusively used to sustain the balloon. A kevlar tripod, made of three tethers attached to the ground, is hung up on the balloon by a secondary cable. At the top of the tripod, 160 m high, a metal cylinder is suspended, the L. S. O. (Lightning Strike Object), designed to be hit by triggered lightning flashes. The sensors devoted to electric field measurement aloft are hooked up on the secondary tether between ground level and the maximum height, roughly 200 m below the altitude of the balloon, so the latter does not influence the upper sensor.

2.2 THE ELECTRIC FIELD SENSORS

The instruments used to detect the local electric field are displayed on figure 2. A standard shutter field mill, flush with the ground, measures

the surface field. It delivers a 1000-Hz voltage whose amplitude is modulated by the electric field. A fast amplitude detection provides a DC voltage proportional to the field. An in situ calibration is performed to relate the output voltage to the applied electric field, by using an electrode parallel to the instrument ground plane and connected to a high voltage generator.

The other sensors shown on figure 2 are devoted to ambient electric field measurement in altitude. The requirements taken into account for a correct design are of several types: (1) Self-contained unit working by telemetry, (2) Shape producing a local field enhancement as weak as possible, (3) Compensation system for the electric field created by the net charge on the apparatus.

The geometry and general configuration: According to various authors and specially Clarke [8], Rust and Moore [9], Few et al. [10], the instrument housing is made to be close to a conductive sphere in order to obtain the most uniform curvature possible and to minimize the emission of space charge. Thus the conducting sphere, 0.25 m in diameter, contains the whole system assembly: electronic circuits, rotation motor, batteries. On the other hand, since it has been decided to measure only the vertical component of the electric field, a double field mill configuration is adopted (fig. 3). Thus two identical field mills are symmetrically located at the top and the bottom of the sphere with a common rotation axle driven by a small electric motor. As it has been previously described [2], the combination of the signals provided by the two field mills achieves the elimination of the field component created by the net charge on the instrument. The principle of this elimination is schematized on figure 3. The vertical component of the ambient field creates, at the top and the bottom of the spherical sensor, equally enhanced fields of the same polarity, E^a . On the other hand, the net charge on the instrument generates, at the same places, fields of opposite polarity whose common intensity is E^n . So the upper field mill measures $E^a + E^n$, while the lower one measures $E^a - E^n$. Making the difference between the signals delivered by both mills eliminates E^n . This procedure is achieved by the electronic circuit and requires the adjustment of the amplification during calibration.

Rotors and stators of each field mill are divided into ten sectors, which provides a signal frequency (500 Hz) equal to ten times the rotation frequency (50 Hz). The transmission antenna is a dipole, made of the two half-spheres that constitute the sensor housing. The sphere is mechanically coupled to the suspension system of the tether using a Cardan coupling device that provides two degrees of freedom and the weight balance of the whole instrument keeps it in the vertical position.

The electronic circuitry: The modulation circuit is designed to provide an AC voltage whose frequency is modulated by the electric field signal. This voltage itself modulates in frequency a commercial transmitter built by C.E.A.F. (Construction Electronique André Fortier), whose frequency is crystal stabilized between 400 MHz and 406 MHz and power limited to 50 mW.

The modulation block diagram is indicated on figure 4. It uses a synchronous detection device whose reference signal is provided by a Light Emitting Diode/Photo Transistor system coupled with a rotating screen identical to and synchronous with the field mill rotors. Each field mill is associated with an independent circuit, both signals being combined at the end of the processing. As Winn and Moore [11] did with their instrumented rocket, we use first, in both circuit associated to each field mill, a charge amplifier

that provides an output voltage proportional to the induced charge on the electrode. After DC elimination and variable gain amplification, a double fast peak detector samples both positive and negative peaks. After summing, the signal is applied to a double sample hold circuit triggered by the reference signal for synchronous detection. A difference amplifier finally provides the peak to peak value proportional to the electric field, including its polarity. This final signal is combined, in a difference amplifier, with that provided by the circuit originated from the other field mill, in order to eliminate the field component created by the net charge on the apparatus. The output voltage, proportional to the ambient field, is converted into frequency, thanks to a V.C.O. (Voltage Controlled Oscillator) whose output signal modulates the FM transmitter already mentioned. The V.C.O. central frequency is 15 kHz and the corresponding bandwidth 10 kHz. Three different sensitivities have been chosen for each sensor: ± 150 kV/m, ± 100 kV/m and ± 50 kV/m. The calibration of each sensor in real conditions (telemetry) is performed at the laboratory.

2.3 THE RECEPTION SYSTEM

The ground station (fig. 5) is designed to receive five simultaneous channels transmitting within the frequency range: 400-406 MHz. The directional antenna is connected to a wideband UHF preamplifier. It is followed by a frequency converter whose local oscillator frequency is such that the output signals frequencies fall within the range of a commercial FM tuner. Each of the five tuners whose input are connected in parallel, delivers a frequency modulated signal corresponding to a given altitude. A P.L.L. (Phase Locked Loop) restores the voltage proportional to the electric field detected by each sensor. Finally the reception system provides five simultaneous field variations with a response time of about 2 ms. The surface field evolution detected by the standard field mill located by the ground station is digitized in the processing system along with the variations aloft: its response time is 1 ms. The six simultaneous evolutions are numerically processed in order to provide clear and simple real time display as well as delayed treatments. In parallel with the numerical data processing, an analog tape recorder is used to record the multilevel simultaneous field data at 1 ms time resolution. This analog recording carries out the storage of the data at the shortest time resolution of the sensors, while the digitizer and numerical data processing is performed with a 10-ms time resolution.

2.4 THE DATA PROCESSING

The whole numerical processing is performed using a Hewlett-Packard 1000/A600 minicomputer and a Vectra ES Hewlett-Packard microcomputer in the terminal configuration. The system digitizes the six channels data with a 12-bit resolution and a rate of 100 samples per second and achieves two kinds of procedures renewed every second: a real time display and a relevant storage (53 Megabytes hard disk capacity) for subsequent utilization.

The real time procedure consists in fact in displaying the six values of the field intensity at a reduced rate of one instantaneous value per second, at the end of each acquisition sequence. This is performed on the color screen of the Vectra microcomputer and presented under three different formats (fig. 6): (1) instantaneous numerical values of the field at all levels

(upper left), (2) simultaneous time evolution of multilevel field intensities (lower left), (3) profile evolution (right). These three different modes of representation provide complementary information about the electric field distribution within the first hundreds of meters, about the structure of the charge layer above ground and about the electric field evolution at each level.

3. EXAMPLES OF APPLICATIONS

3.1 LIGHTNING FLASH TRIGGERING

In agreement with previous results, it has been observed during Florida 89 experiment that the electric field is usually much higher in altitude than at the ground. Figure 7 shows the simultaneous variations of the electric field at ground level and at 603 m recorded during the thunderstorm of August 10 between 23:30 and 00:30 (Universal Time). During this event the electric field was measured at several levels up to 603 m. After the balloon rising the electrical activity was detected on the site at about 23:00. The recording presented on figure 7 stops at 00:30 when the last sensor stopped functioning (because of normal power supply failure), but the thunderstorm activity was not finished. Both available field variations undergo discontinuities corresponding to several lightning flashes, five of them being triggered by rockets (23:47, 23:53, 23:58, 00:04 and 00:30). The sign convention corresponds to a positive intensity when the field vector is upward. The observation of such a graph calls for some remarks:

(i) The field intensity detected at 603 m is always positive whereas the one measured at the ground can reverse after a lightning flash.

(ii) The surface field intensity does not exceed about 5 kV/m while that at 603 m reaches 65 kV/m (23:58). This large difference is the result of stabilizations of the surface field intensity for a few minutes during which the field continues to increase at 603 m.

(iii) When the surface field intensity reaches large values after a lightning flash it decreases very quickly. Generally after the same discontinuities the field at 603 m does not undergo this sort of decrease, its intensity varies little during the minute following the lightning flash responsible for the discontinuity. Many examples illustrate this observation: each triggered flash and some natural flashes at 23:34, 23:46, 23:52 and 00:09.

(iv) The field discontinuities corresponding to lightning flashes are larger in altitude specially when the intensity of the field at ground level becomes important.

All these remarks can be interpreted in terms of corona ions production at ground level. During the development of the thunderstorm activity, these ions progressively build up a charge layer that keeps the surface field from reaching high intensities. Consequently, its value is no longer directly related to the thunderstorm activity. For example at the beginning of this recording, at 23:30, the field intensity is close to 2 kV/m at ground level

and reaches 15 kV/m at 603 m. At this moment the difference between the two levels can be attributed to corona ions previously released. At the end of this recording, just before 00:30, the difference is much larger, since the field intensity is again close to 2 kV/m at the surface, whereas it exceeds 50 kV/m at 603 m. As a matter of fact, the field intensity measured at ground level is the sum of two components, one related to cloud charges and the other due to the whole charge layer between the ground and the cloud [4 and 5]. The value of this intensity is generally used in order to evaluate the proximity of the thunderstorm or its development stage. In the case of lightning flash triggering for example the surface field intensity is considered as the criterion to launch a rocket [12]. According to figure 7 the fifth flash (00:30) was triggered with a surface field intensity very close to 2 kV/m. However the one detected at 603 m reached 50 kV/m which means good conditions to produce a flash. This case shows that a flash can be triggered even if the field is low at ground level. We can suppose that a triggering could be successfully attempted with a surface field intensity close to zero or even slightly negative. Such conditions appear on the variation of figure 7 at 00:07, 00:14 and 00:19. At such moments there is a discrepancy between the surface field intensity and the real thunderstorm electrification better accounted for by the altitude electric field. The detection of the electric field at several hundreds of meters above ground is therefore helpful for lightning flash triggering. Until now, thanks to the good experience of specialists, the success rate in lightning flash triggering reaches the satisfactory value of 70 % (percentage of technically successful launches that trigger lightning) [12]. However with the new information constituted by the field values aloft more numerous favorable occasions could be considered specially at the end of thunderstorms when the surface field component due to the charge layer is important. As a matter of fact the number of flashes triggered during a thunderstorm could probably be greater.

3.2 VERTICAL ELECTRIC FIELD DISTRIBUTION

The measurement system provides electric field variations during a thunderstorm at six levels including the ground. The data obtained can be displayed in two different ways, in terms of simultaneous electric field variations at several levels or in terms of evolution of the electric field profile. In the present paper we choose to point out the second aspect, the first one needing a more extensive development and the display of several graphs in order to provide reasonable legibility and clearness.

The vertical electric field profile is therefore available at any instant during the thunderstorm. It permits to clearly visualize the vertical electric field distribution. It is a way to characterize the electrical conditions of the medium where the lightning leader propagates. The time resolution of these profiles corresponds to that of our sensors i. e. 2 ms. Consequently it is possible to study the evolution of the profile at any time resolution larger than 2 ms. This kind of study will be interesting to develop during a very brief phenomenon like a lightning flash. Figure 8 displays an example of field profile evolution corresponding to a natural flash during the thunderstorm of August 10. Five levels are used and the time separating two consecutive profiles is 10 ms. This graph shows for example that the electric field varies during a longer period of time in altitude than at ground level. This observation can be explained again by corona ions generation during the field change produced by the flash [13]. The evolution

of the vertical field profile can be studied during other periods of the thunderstorm: regeneration after a lightning flash or the whole thunderstorm lifetime.

Figure 9 displays two evolutions of this profile beginning at 23:10 on August 10. Unfortunately in this case the resolution of a given profile is limited by the number of working levels available and consequently decreases during the thunderstorm (while sensors stop functioning because of power supply failure). As a matter of fact the evolution 9A that lasts 23 minutes uses five-level profiles and the evolution 9B that lasts 48 minutes uses only three levels.

In figure 9A it clearly appears that only the lower part of the profile (below 436 m) evolves in such a way that the vertical gradient of the electric field increases during this period. In contrast, this gradient stays close to zero within the upper part. In the case of the second evolution (fig. 9B) the steepening of the vertical field profile indicates a strong increase of the electric field vertical gradient due to the building up of the charge layer. Although the global evolution of the profile corresponds to an increasing slope, some anomalous profiles (for example n° 7) are observed. They only denote the occurrence of a lightning flash that suddenly reduces the electric field everywhere. It is easy to check that the development of the charge layer keeps the field intensity at the surface and at 80 m from reaching high values. As a matter of fact, at these levels it does not exceed respectively 5 and 10 kV/m. Furthermore, by the end of the period displayed on figure 9B (after profile 6), a field difference appears and increases between the two upper levels. This phenomenon indicates that corona ions from the charge layer probably reach the 436-m level.

3.3 THE SPACE CHARGE DEVELOPMENT AND EVOLUTION

The multilevel electric field distribution can be used in order to describe the evolution of charge layer above ground. However special conditions must be fulfilled and some hypotheses about charge motions must be formulated to make it possible to deduce charge and current densities from electric field measurements.

The calculation of charge density using Gauss's law requires an essential condition on the surface producing corona ions. This surface must be homogeneous and its dimensions large compared to the height where the calculation is performed. A recent study about this experiment [14] shows that the local wind and vertical drift of the ions lead to this condition fulfillment. On the other hand a calculation of a possible "distance effect" influence indicates that this effect can be neglected in a first approximation.

This procedure has been utilized to compute the average charge density evolution within the various layers defined by the multilevel measurements. We essentially consider the layers whose lower limit is the ground. In order to smooth the evolution of the charge density within the above defined layers, we plot its variation averaged over periods of 350 seconds, versus time, during the most active stage of the thunderstorm (50 minutes duration). This procedure reduces the fluctuations due to the field changes caused by flashes and provides a better observation of the slow evolution of the charge layer. Figure 10 displays four diagrams corresponding to the three layers limited by the ground and the upper layer 436-603 m. The charge density within the lower layer (0-80 m) fluctuates around a rather stable value of about 0.3 nC m^{-2} (fig. 10A). This stationary behavior indicates that, during

this period, the upper charge outflow (conduction and/or convection current density) roughly compensates for the lower charge inflow (ground corona current density). Within the layers 0-436 m and 0-603 m, the charge density progressively increases and tends to 1 nC m^{-3} (fig. 10B and 10C). It logically stabilizes first within the 0-436-m layer, which seems to show that a substantial current crosses the 436-m level and penetrates the upper layer. The variation of the average charge density between 436 m and 603 m shown on Figure 10D confirms this fact. Until 23:38 no charge appears above 436 m. Subsequently the density rapidly increases and exceeds 0.5 nC m^{-3} by the end of the period. This observation does not give any information about the nature of the electric current that flows through the 436-m level, conduction or convection, but it clearly reveals its presence.

The present dynamical analysis shows that the charge layer that develops above ground during thunderstorms does not always stay confined close to the ground. Previous papers by Standler and Winn [4] and by Chauzy and Raizonville [2] reported layer depths ranging about 150 to 200 m. Standler and Winn evaluated average charge densities from 0.5 to 1 nC m^{-3} , quite close to those estimated here. Chauzy and Raizonville measured local maximum charge densities ranging from 3 to 6 nC m^{-3} , that are consistent with the average densities computed over deeper layers.

4. CONCLUSION

The system described here was especially designed to be used for research purposes. It was tested during the FLORIDA 89 experiment at Kennedy Space Center and successfully detected the time evolution of the vertical electric field profile above ground during thunderstorms. Such a measurement technique makes it possible to study the formation and development of the space charge layer created at the ground by corona effect. It also provides the characteristics of the field structure in which a cloud to ground lightning flash propagates. In a near future, it is intended to function as main tool of an experimental program on the evaluation of electric currents between cloud and ground. It will be interesting to establish the balance of the various components of the slow exchange of electric charges between cloud and ground, this exchange being part of the thundercell electrification: displacement current, corona current, conduction current, convection current, and precipitation current.

This equipment could also be of some help associated with a thunderstorm warning system. As it has been extensively observed [5 and 14] the raw intensity of the surface electric field is a good indicator of a thunderstorm approach or development, but it is not quite able to evaluate the imminent risk for a given site to be stricken by lightning. The evolution of field intensity aloft provides a useful complementary information about this risk.

Acknowledgments: We are grateful to the Direction des Recherches Etudes et Techniques for supporting our participation in Florida 89 experiment. We appreciate the support and the help of W. Jafferis in the organization of the experiment at NASA Kennedy Space Center. We also wish to thank the members of ONERA and CENG groups whose participation was very helpful.

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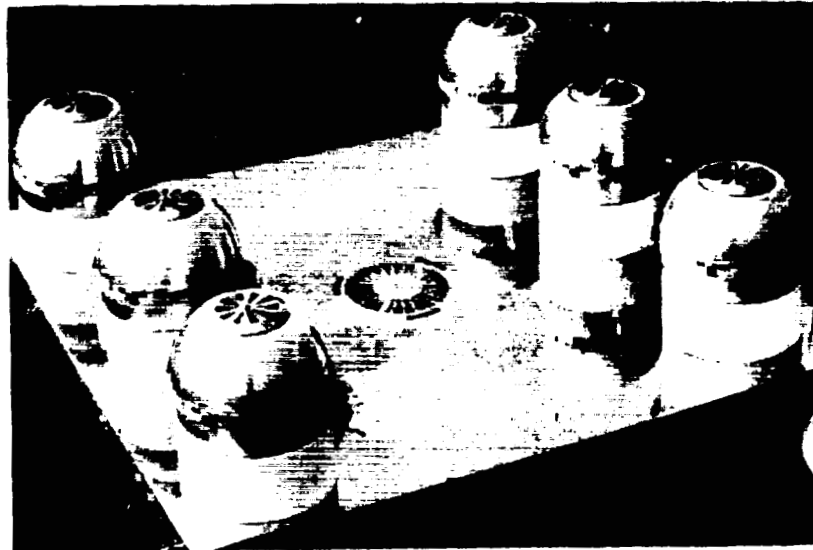


Fig. 2 : The six electric field sensors designed to be suspended from the balloon and the standard field-mill (center) flush with the ground.

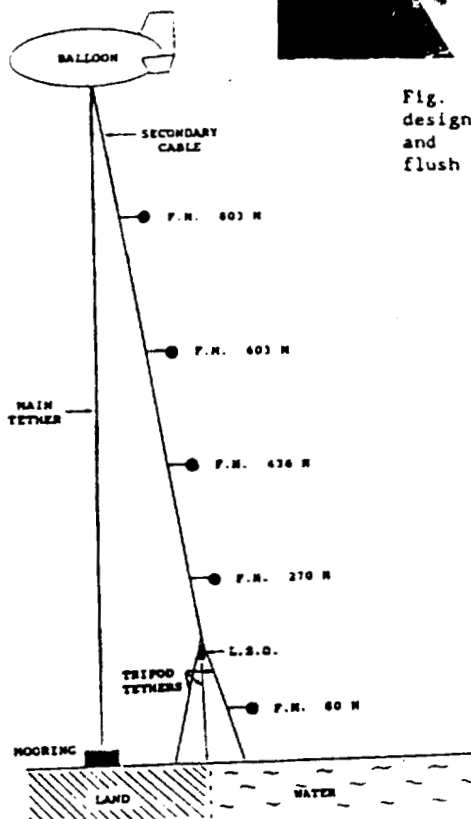


Fig. 1 : Sketch of the sensors (F.M.) distribution along the tether when the system is in the measurement position.

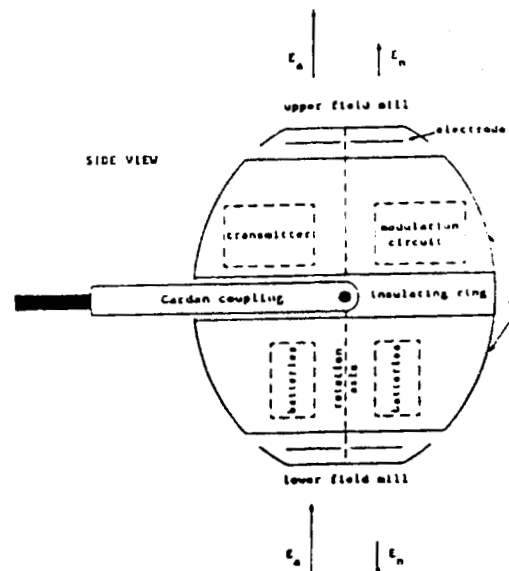


Fig. 3 : Diagram of each electric field sensor geometry.

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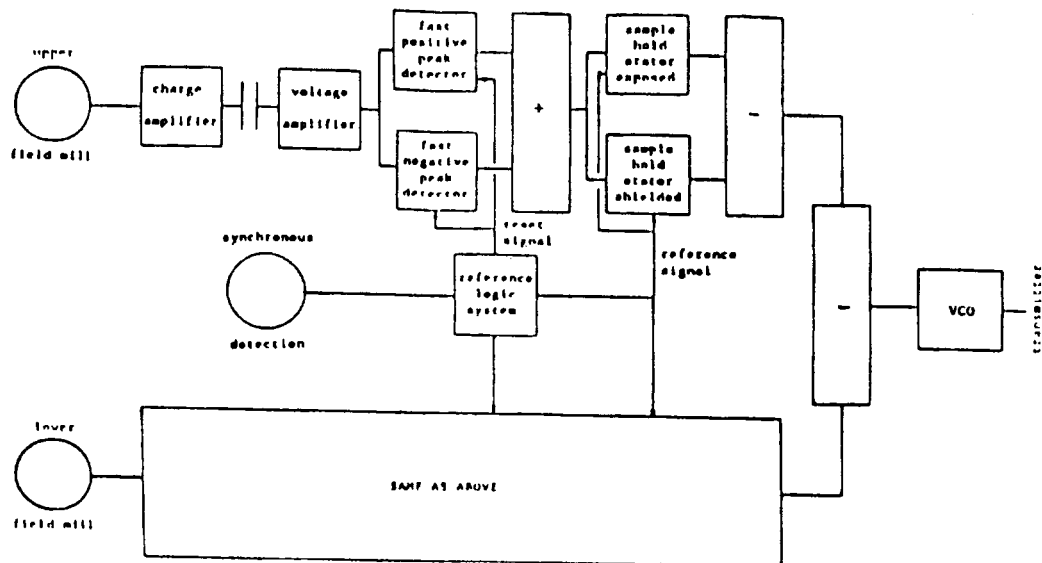


Fig. 4 : Block diagram of the modulation circuit of each electric field sensor.

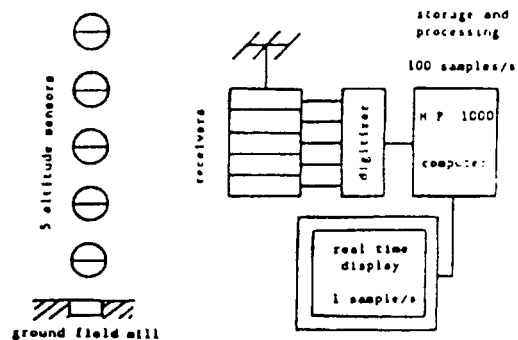


Fig. 5 : Ground reception station sketch-plan.

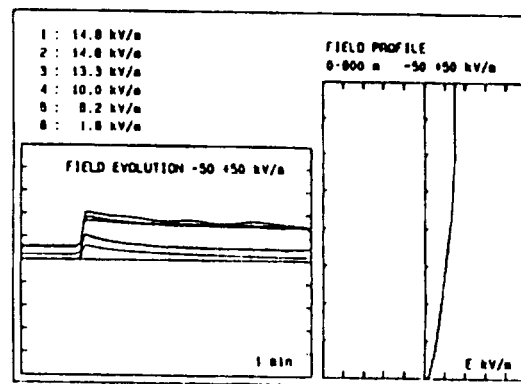


Fig. 6 : A simulation of the computer screen during the experiment at Kennedy Space Center. Upper left: the six instantaneous values. Lower left: the evolution of the electric field at six levels during one minute. Right: the instantaneous vertical profile.

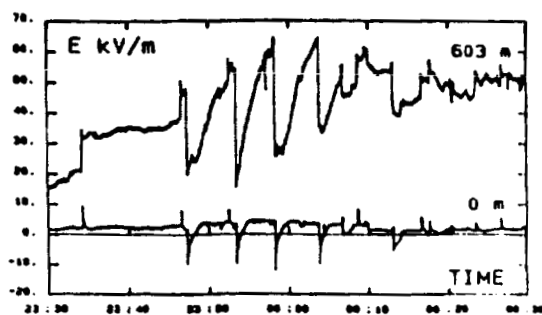


Fig. 7 : Electric field variations measured at ground level and at 603 m beneath a thunderstorm on August 10, versus universal time. During this period five lightning flashes (89-10, 89-11, 89-12, 89-13 and 89-14) were triggered at respectively 23:47, 23:53, 23:58, 00:04 and 00:30.

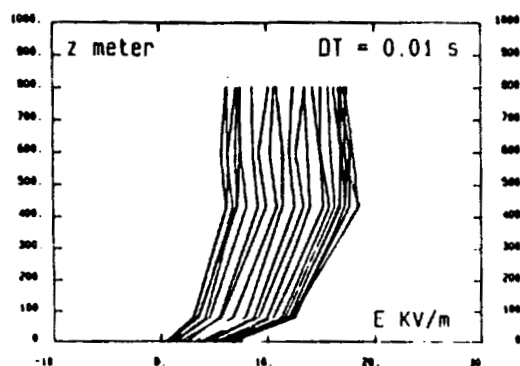


Fig. 8 : Evolution of the electric field profile composed using five level data during a natural lightning flash. The time interval between two consecutive profiles is 1 ms.

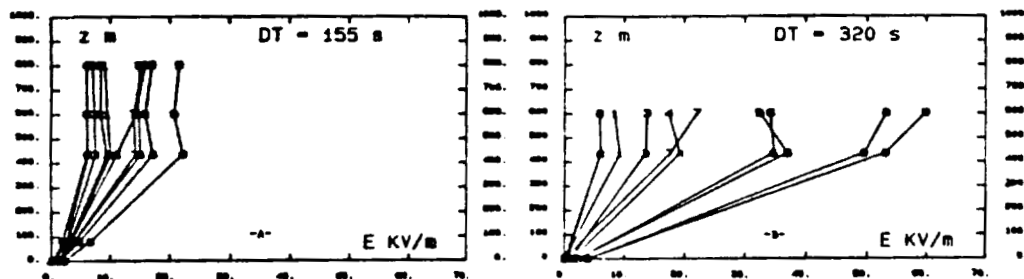


Fig. 9 : Evolution of the electric field profile constructed with five levels and during 23 minutes (case A between 23:10 and 23:33) and with three levels and during 48 minutes (case B between 23:10 and 23:58).

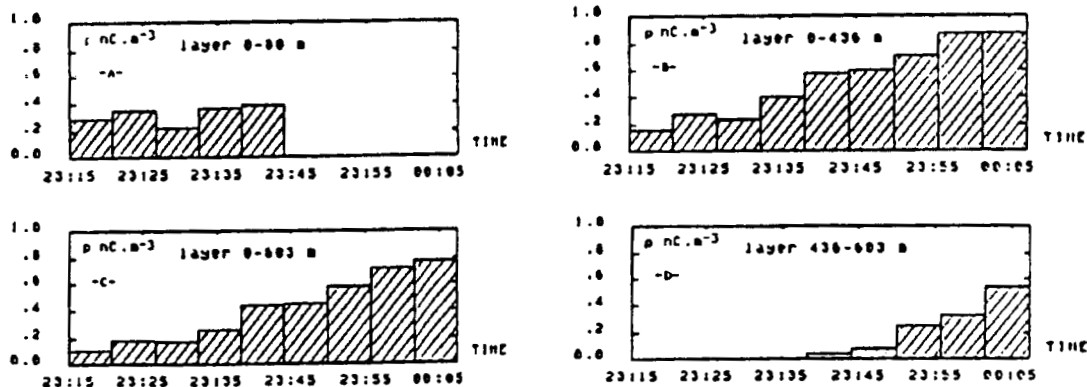


Fig. 10 : Evolution of the average charge density versus universal time during the thunderstorm within four layers: A : 0-80 m, B : 0-436 m, C : 0-603 m and D: 436-603 m. The average charge density is calculated for equal time intervals.

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